EXPLOSIVE PULSED POWER EXPERIMENTS AT THE PHILLIPS LABORATORY

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Abstract

The application of pulsed power technology to advanced mission scenarios increasingly involves achieving higher peak power and energy while shrinking the deployment package. The inherent high energy density of explosives make them an obvious candidate for applications requiring extremely compact, single shot pulsed power drivers. However, explosive flux compression generators tend to be rather slow, low impedance, high current devices, while the loads of interest typically present a relatively high impedance and require short, high voltage pulses. In this paper, the results of experiments involving helical explosive generators and pulse shaping/impedance matching systems are discussed.

Introduction

Air Force missions utilizing pulsed power technology increasingly require the system to fit into smaller and lighter packages for deployment, and the pulsed power subsystem often represents the same or greater fraction of the payload package as the load. The energy density (and therefore size and weight) of a given pulsed power system is ultimately determined by material limitations: For electrostatic storage (i.e., capacitive) the limit is electrical breakdown properties, for inductive and inertial energy storage it is mechanical strength. Chemical energy storage generally represents high energy density (for example, an automobile battery stores several megajoules), but the rate at which the energy can be extracted is reaction rate limited and is generally slower than of interest for many applications. A notable exception is high explosives, which provide extremely high energy density (~4 MJ/kg) and discharge times which are suitable (usually with further conditioning) for the desired applications. Helical explosive flux compression generators (FCGs) generally provide high current and energy gain. However, they are low impedance current sources and require power conditioning to match the generator to high voltage, high impedance loads of interest. Additionally, while the discharge time of helical FCGs is of the order of microseconds to tens of microseconds, many loads require fast rise times (~100 ns) and relatively short pulse width (~1 μs). Thus the pulse conditioning system often must provide both temporal and impedance matching between the FCG and the load.

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14. ABSTRACT
The application of pulsed power technology to advanced mission scenarios increasingly involves achieving higher peak power and energy while shrinking the deployment package. The inherenthigh energy density of explosives make them an obvious candidate for applications requiring extremely compact, single shot pulsed power drivers. However, explosive flux compression generators tend to be rather slow, low impedance, high current devices, while the loads of interest typically present a relatively high impedance and require short, high voltage pulses. In this paper, the results of experiments involving helical explosive generators and pulse shaping/impedance matching systems are discussed.

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The Phillips lab compact explosive pulsed power program is tasked with providing a pulsed power system to power a high voltage, high impedance load with a fast rise time and a pulse width of 1 μs. The general approach taken for this system consists of a compact helical generator driving a pulse conditioning system. The pulse conditioning system may be comprised of a switched-primary pulse transformer, a direct acting opening switch (either an exploding wire fuse or an explosively formed fuse), or either of the above with a nonlinear resistor to achieve the required pulse shape. Additionally, a peaking capacitor may be required ahead of the load to achieve the required rise time.

These various pulse conditioning schemes are presently being investigated at the Phillips Laboratory, both computationally and experimentally. In all of the schemes, some form of opening switch will be required, likely a fuse, and experiments are underway to investigate the properties of aluminum and copper fuses. In addition, a full scale experimental system to drive the pulsed conditioning systems in the laboratory (i.e., without the need for an explosive generator drive) is being constructed.

Explosive pulsed power experiments began at the Phillips Laboratory in the summer of 1995 with joint pulsed magnetohydrodynamic experiments with Sandia National Labs. These experiments, which are described in [1], spurred the development of explosive experiment infrastructure at the Phillips Laboratory. The explosive experiments to be described in this paper were begun approximately one year ago. These experiments centered around the use of a simple helical explosive generator to drive further development of explosive experiment infrastructure, develop diagnostic techniques, and to provide benchmarking data for design and analysis codes.

Experimental Facilities

The Phillips Laboratory explosive pulsed power facility is located in a remote box canyon and is designed to accommodate explosive experiments of up to 1000 lb of high explosives. The experimental facility includes a 200 kJ, 10 kV capacitor bank for providing seed flux for FCGs. The output of this bank is fed through fifty low inductance coaxial cables to a detonator driven switch located near the explosive pad. The current is then fed to the explosive containment structure on the pad. Capacitor discharge units (x-units) for driving detonators are located in concrete culverts near the pad. Diagnostic coaxial and fiber optic cables terminate in a small diagnostic shed on the pad. Another shed located on the pad houses a Beckman and Whitely 189 high speed framing camera, which is used for optical diagnosis of explosive events. Electrical and optical signals are fed to a screen room located in the explosive facility. This screen room houses controllers for the capacitor bank and x-units, 28 digitizer channels, timing and delay systems, and a computer control and data acquisition system. A streak camera records signals from a crushed fiber optic diagnostic system, which is used to provide a temporal record of the armature impact with the generator stator (this diagnostic will be described in detail below.)

Experiments

The first explosive experiments performed in support of the compact explosive pulsed power program involved the detonation of armatures, which compress the seed magnetic flux within the FCG. These armatures consisted of 6.4 cm i.d. 6061 seamless aluminum tubes approximately 45 cm long. Armatures of varying wall thickness were fired in order to determine the minimum wall thickness consistent with the desired armature performance (factor of two expansion with negligible armature breakup and jetting). After machining, these armatures were annealed to a T3 hardness and were loaded with approximately 7 lb of C4 high explosive. The principle diagnostic employed in these experiments was the high speed framing camera described above.

So called argon candles were used to provide illumination of the armature during expansion. These devices consist of a plywood box with a lexan window, filled with atmospheric pressure argon and lined with detasheet explosive. The explosive detonation shock ionizes the argon fill, producing a brilliant light pulse

In addition to the high speed photography, electrical impact pins and crushed fiber diagnostics were used to provide temporal information about the armature arrival at the factor of two expansion point. The electrical impact pins were mounted in a steel anvil below the armature, with the ends of the pins located radially at the desired expansion points. The pins consist of two coaxial electrodes biased to a potential of approximately 300 volts. Upon impact, the armature shorts the pin, which results in a pulse being recorded via a multiplexer/biasing circuit. While the impact pins provided reasonable values for both the explosive detonation velocity (i.e., the axial velocity of the self consistent armature expansion) and the radial expansion velocity (estimated from the Gurney velocity [2]), there is some evidence that the absolute timing of the impact pins is early relative to the other diagnostics. We believe that this may be due to premature shorting of the pins by the air shock wave in front of the armature outer surface.

The crushed fiber optic diagnostic utilizes the black body radiation produced by optical fibers under extreme impact pressure. The fibers are arranged parallel to the armature, such that the light produced by the impact is transmitted by the remaining (unimpacted) fiber. The light output is recorded using the streak camera. Typically, four to six fiber signals are recorded using the camera, along with the light output from a pulsed LED, which gives a fiducial timing signal to allow correlation of the crushed fiber diagnostic with the overall experiment timing.

Once the optimal armature wall thickness was determined, magnetic flux compression experiments were performed with simple helical FCGs which were designed primarily for simulation code benchmarking. These generators used 32 and 64 turn stators with an i.d. of 15.2 cm and a length of 40 cm. The generator initial inductance was 55 and 200 μH, respectively. The generators drove load inductances of 150 to 200 nH, with an initial seed current of from 10 to 25 kA. The diagnostics included the impact pin and crushed fiber diagnostics (with the pins inserted between stator turns and the fibers lying axially along the stator) with the addition of current and voltage measurements. The current diagnostics consisted of load Rogowski coils, while the voltage was measured with resistive dividers across the load. Additionally, the voltage across the last three turns of the generator was measured using a Pearson coil to record the current through a calibrated resistor across the turns.

The voltage waveforms for a typical shot are shown in Fig. 1. These data are for a 32 turn generator seeded with 10 kA. The generator current gain is approximately 35. The crushed fiber impact probe data in shown in Fig. 2 along with the dI/dt across the load (i.e., unintegrated Rogowski coil signal). The light output from the crushed fibers in these experiments appeared as discrete pulses, which we assume to correspond to the discrete windings of the stator (this will be discussed further below). The horizontal bars on the crushed fiber data represent the uncertainty of the location in time of the light signal due to the non zero width of the light pulse. Comparison of the dI/dt signal with the crushed fiber data presented in Fig. 2 clearly shows that the generator output voltage decays several turns before the armature reaches the load end of the generator. This may be due to high voltage breakdown within the generator or breakup of the armature (or, in fact, breakdown induced by armature breakup). In any event, the loss of several end turns of the generator has occurred in nearly every experiment and represents a major loss of current and energy gain in these devices. We are addressing these problems in next generation FCG designs

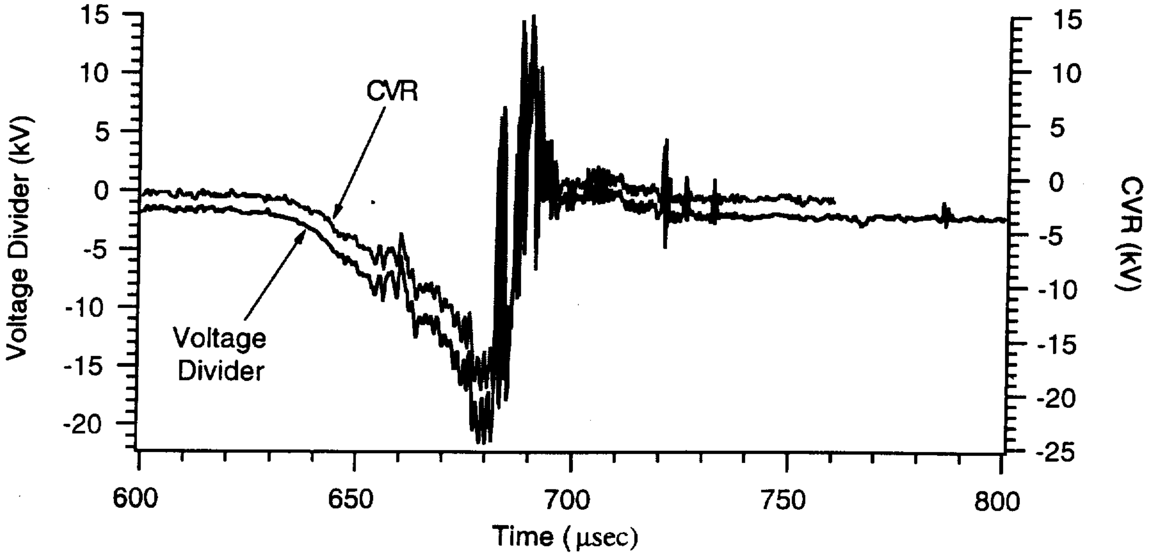

Figure 1. Voltage divider and current viewing resistor (CVR) traces for a 32 turn helical explosive generator as described in the text. The initial current was 10 kA.

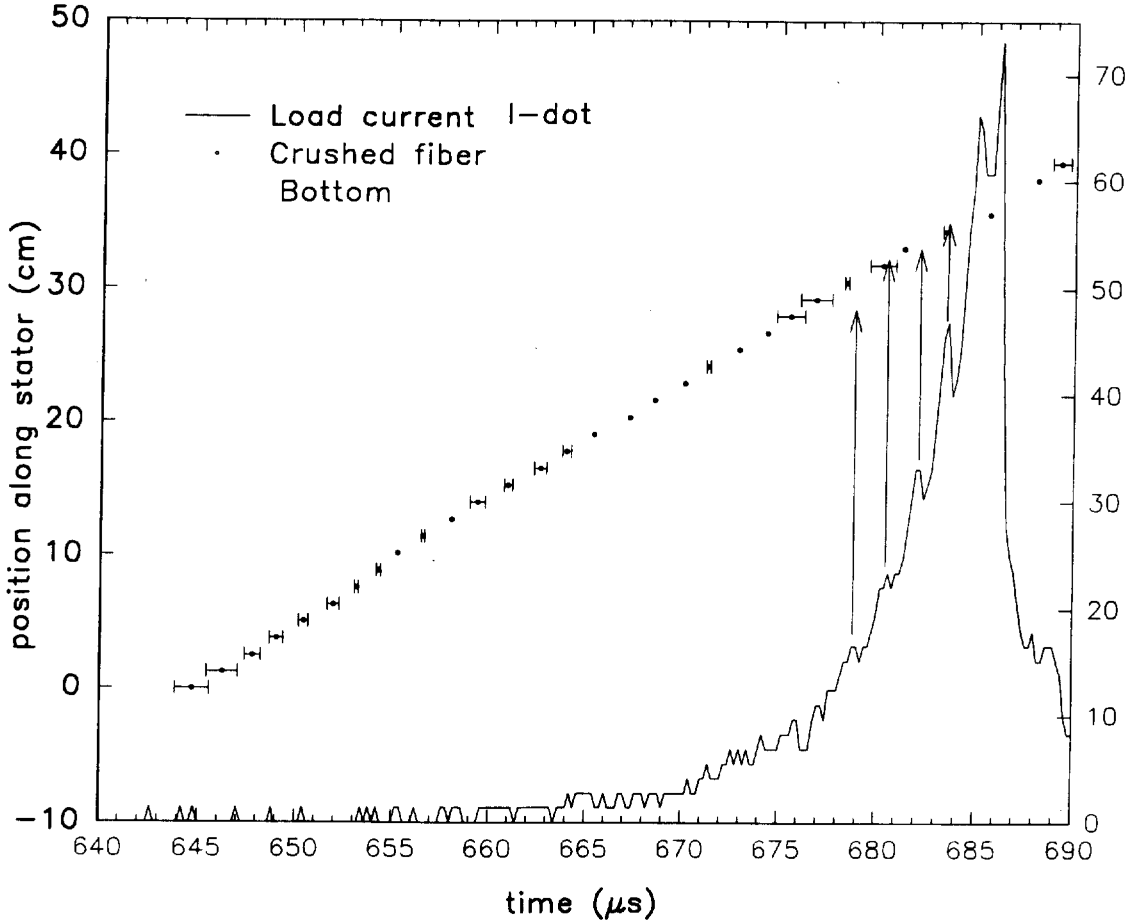

Figure 2. dI/dt and crushed fiber impact data for a 32 turn helical explosive generator. This shows the apparent loss of generator performance near the load end of the device.

As mentioned above, the crushed fiber diagnostic light output from the generator experiments gave discrete light pulses, with the number of pulses equaling the number of windings in the generator. Additionally, assuming that the pulse spacing is related to the physical turn spacing, the armature impact axial velocity determined from the crushed fiber diagnostic is very close to the C4 detonation velocity.

In order to test the hypothesis that the light pulses correspond to the discreet turns of the stator, an experiment was designed in which the stator was replaced with a series of discrete rings with variable spacing. The light output from the crushed fibers upon detonation was pulsed, with the temporal spacing of the pulses corresponding well with the explosive detonation velocity in the region with large ring spacing (1.27 cm on center). The light output inexplicably disappeared in the region with narrow ring spacing (0.32 cm on center). There were fibers placed at five azimuths around the ring structure. The position vs time for these fibers, shown in Fig. 3, seem to indicate that the armature is impacting the ring structure in an asymmetric fashion. This may be due to imprecise alignment of the armature in the fixture or nonuniform expansion of the armature during detonation. Experiments are underway to attempt to resolve this.

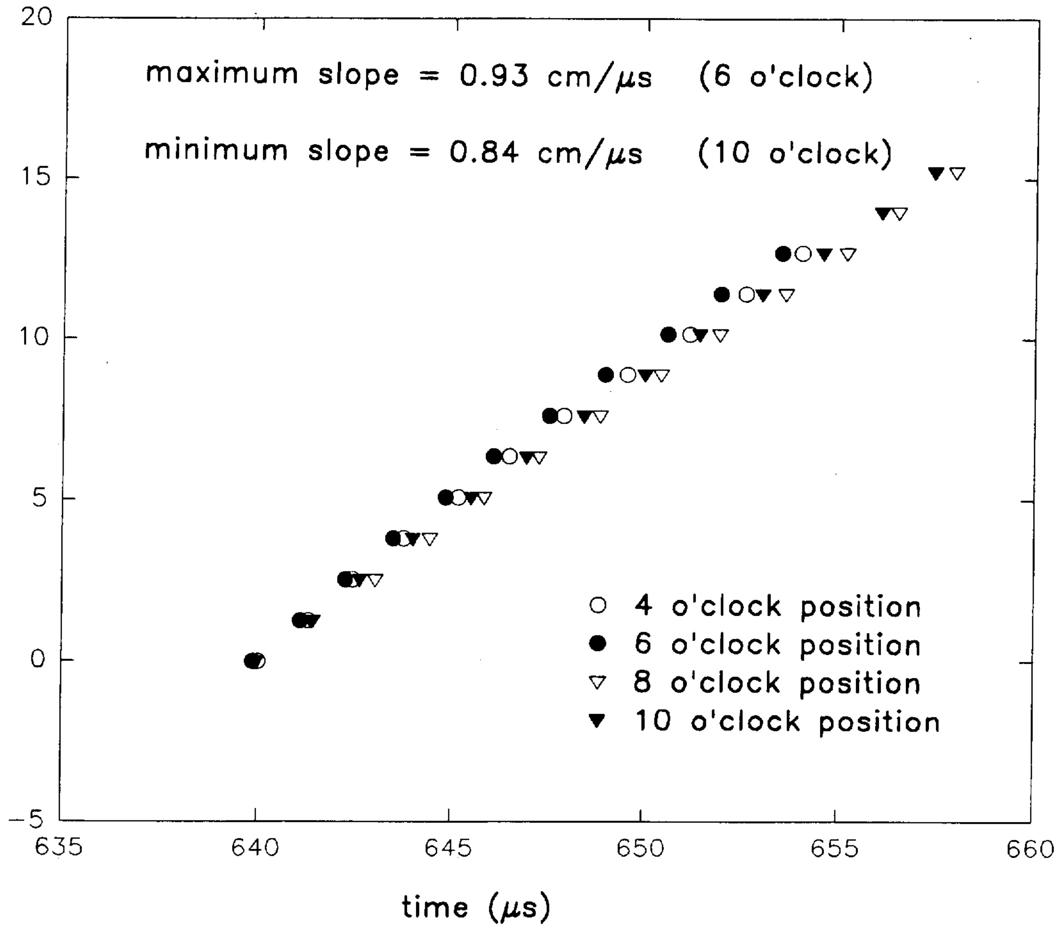

Figure 3. Crushed fiber impact data for several azimuths in the ring test device described in the text. The data show the asymmetry of the armature impact.

Computational Efforts

Several computer codes are used or are in development in support of the Phillips Laboratory explosive pulsed power program. These include circuit codes such as Microcap and circuit-based generator specific design and analysis codes such as CAGEN [3]. Material interface tracking and explosive detonation capability have been incorporated into MACH2, a 2 1/2 dimensional magnetohydrodynamic code. MACH2, and MACH3, the fully three dimensional version under development, are well suited to detailed studies of areas such as armature expansion.

Conclusions

In the Phillips Laboratory explosive pulsed power program we have successfully conducted armature expansion and helical explosive generator experiments. A capacitor based simulation facility is under construction for testing pulse conditioning concepts. The experiments which have been performed to date have achieved the goals of developing explosive pulsed power experiment capability at the Phillips Laboratory, developing diagnostics, and providing benchmarking data for computer codes.

Near term experiments will concentrate on the refinement of diagnostics and improvements of armature and, therefore, FCG performance. The next generation helical FCG design will address the apparent breakdown near the load end of the generator. This generator is being designed to meet the specifications of the ultimate mission.

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References

[1] Agee, F.J., Lehr, F.M., Vigil, M., Kaye, R., Gaudet, J., Shiffler, D., "Explosively-Driven Magnetohydrodynamic (MHD) Generator Studies," Proceedings of the Tenth IEEE International Pulsed Power Conference, pp. 1068-1071, 1995.

[2] Kennedy, J.E., "Explosive Output for Driving Metals," Proceedings of the Twelfth Annual Symposium on the Behavior and Utilization of Explosives in Engineering Design, pp. 109-124, 1972.

[3] CAGEN, Caren Co., 12137 Midway Dr, Tracy, CA 95376, (209) 835-0295.